A request for addition of page 11 of the descOription has been filed pursuant to Rule 88 EPC. A decision on the request will be taken during the proceedings before the Examining Division (Guidelines for Examination in the EPO, A-V, 2.2).

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(54) **Rapidly tunable windeband integrated optical filter.**

(57) A monolithically integrated wideband optical filter which is rapidly tunable to a large number of optical frequencies over a wide optical frequency range comprises two series connected optical filters of different resolutions formed in a semiconductive wafer. A control circuit applies electrical energy to predetermined controllably transmissive waveguides connecting components of the filters defined in the wafer. This tunes the overall filter to a desired one of a plurality of optical frequencies. Application of such electrical energy creates frequency selective pathways through the wafer able to pass one of up to hundreds of selected optical frequencies over the entire bandwidth of a semiconductive medium. This filter is economical to construct and is useful in high capacity, high speed optical communications networks.

FIG. 1

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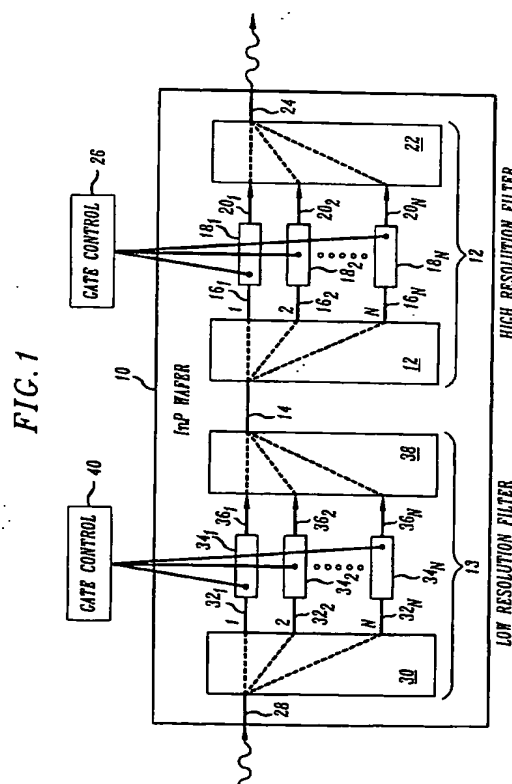
Technical Field

This invention relates to optical communications systems. More particularly, this invention relates to filters used in optical communications systems.

Background of the Invention

The capacity and speed of communications systems may be increased by transmitting information in optical form over networks composed of optically transmissive nodes, fibers, waveguides, and the like. High capacity optical communications systems require that many optical signals be frequency division multiplexed in the components of an optical network. This requires that there be a way of conveniently detecting a single electromagnetic frequency and separating it from a plurality of multiplexed electromagnetic frequencies. An ideal device for detecting a single optical frequency and separating it from a plurality of multiplexed frequencies is a frequency selective optical filter. Until now, there has been no convenient approach to creating a suitable optical filter tunable to a large number of optical frequencies. The performance of prior filters has been limited in terms of tuning speed, frequency selectivity, or tuning range. All of these prior devices also have been expensive to implement.

SUMMARY

Our copending application (herein referred to as Glance 22) entitled Rapidly Tunable Integrated Optical Filter describes a rapidly tunable optical filter fabricated with wide gain bandwidth photonic integrated circuitry. The filter described in the application uses 1xN frequency routing devices such as the multiplexer/demultiplexer devices described in U.S. Patents 5,002,350 and 5,136,671. This filter is rapidly tunable to up to N discrete optical frequencies, where N is the number of branches of the frequency routers used in the filter.

We have found that the number of discrete frequencies to which a filter using frequency routing devices may be dramatically increased by utilizing the periodic routing properties of the frequency routing devices like the ones described in the patents mentioned above. For example, the number of discrete frequencies to which such a filter may be tuned may be up to N^2. A filter in accordance with this invention thus will be able to detect optical frequencies ranging across the entire bandwidth of the semiconductor material used in photonic communications networks. A filter in accordance with this invention will also avoid the possibility of tuning to multiple indistinguishable frequencies separated by a free spectral region defined by the characteristics of the frequency routing devices used in the filter.

In one example of this invention, a wideband filter takes advantage of the periodic routing properties of frequency routing devices to provide detection of a set of discrete frequencies equal to the square of the number of branches associated with the frequency routing devices. Such frequency routing devices of modest size can be used to build optical filters tunable to hundreds of frequencies. Each of these filters may comprise two cascaded optical filters constructed in accordance with the principles of Glance 22.

One of the filters is a high resolution filter and the other of the filters is a low resolution filter. Each filter comprises two 1xN frequency routing devices connected in series by their N branches. An active section, integrated into each of these N branches, is used selectively as either an optical amplifier or a gate. Activation of selected ones of these sections provides a frequency selective route between the input and the output of the filter.

The first filter yields high resolution passbands; the second filter yields low resolution passbands each overlapping one of a group of periodic sets of N high resolution passbands created by the first filter. Activation of predetermined ones of the optical amplifiers selects a particular high resolution passband between an input and an output of the wideband filter in accordance with this invention. Any of N^2 consecutive high resolution passbands ΔF wide can be selected over a tuning bandwidth $N^2\Delta F$, which may encompass the entire bandwidth of semiconductive material used in photonic communications networks.

Tuning of the filter may be done digitally by gating predetermined active sections by using an electrical switch to apply bias current to those predetermined sections. The filter is insensitive to the level of bias current supplied to the gates and thus can be expected to be very stable. Switching between frequencies can be potentially made at nanosecond speeds by using fast electrical switches.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of an example of a wideband tunable filter in accordance with this invention.

FIG. 2 is a diagram illustrating the details of the frequency routing devices shown in FIG. 1.

FIG. 3 shows the frequency characteristics of the high resolution filter and the low resolution filter shown in FIG. 1.

FIG. 4 illustrates a representative relationship between a low resolution passband and a high resolution passband to which the two filters in FIG. 1 must be respectively tuned so that the device of FIG. 1 is sensitive to a particular frequency F_{ij} which falls within both passbands.

DETAILED DESCRIPTION

FIG. 1 shows an example of an optical filter which is rapidly tunable over a wide frequency range. It is composed of a high resolution optical filter and a low resolution optical filter both containing integrated frequency routing devices. It is also composed of a number of waveguides for carrying optical signals and a number of optically active sections for providing optical amplification. These structures may be monolithically integrated on a semiconductive wafer. They may be created by means of known photolithographic techniques.

FIG. 1 illustrates a wafer 10 made of a semiconductive material such as an indium phosphide material such as InGaAsP. A 1xN frequency routing device 12 may receive N multiplexed input optical frequencies F_1, F_2, ..., F_N on a single input waveguide 14 defined on the wafer 10. The frequency routing device 12 demultiplexes the input optical frequencies and directs each one of those frequencies into a separate output waveguide connected to the output of the frequency routing device 12. Specifically, frequency F_1 is directed to the output waveguide 16_1, frequency F_2 is directed to the output waveguide 16_2, and so on up to frequency F_N which is directed to output waveguide 16_N. Each of the output waveguides 16_1, 16_2, ..., 16_N is directed to the input of a doped section of waveguide with controllable optical transmissivity. Specifically in FIG. 1, an output waveguide 16_1 is directed to the input of an optically active section 18_1, an output waveguide 16_2 is directed to the input of an optically active section 18_2, and so on up to an output waveguide 16_N directed to the input of an optically active section 18_N.

The outputs of the active sections 18_1, 18_2, ..., 18_N are connected to respective input waveguides 20_1, 20_2, ..., 20_N of a Nxl output frequency router 22. The frequency router 22 will multiplex the single frequencies appearing on the N input waveguides onto a single output waveguide 24, if all of the active sections between the input router 12 and the output router 22 are activated with electrical energy. If only one of the active sections is stimulated with electrical energy, then only the frequency flowing in that activated section will appear on the output waveguide 24. The device shown in FIG. 1 thus acts as an optical filter for the multiplexed input frequencies appearing on waveguide 14 when appropriate active sections are stimulated. Accordingly, a digital gate control circuit 26 is provided for the structure of FIG. 1 which selectively applies electrical energy to predetermined ones of the sections between the frequency routers so that unwanted frequencies in the input stream to the device of FIG. 1 may be suppressed and one or more desired frequencies may be obtained from the output of the device of FIG. 1. As shown in FIG. 3, the filter 12 in FIG. 1 is dimensioned to give high resolution pass-

bands separated by a frequency interval ΔF. There are periodic sets of such passbands identified as free space regions FSR in FIG. 3. Each of the sets of passbands comprises N passbands. The sets of passbands are thus spaced by an FSR of $N\Delta F$. These sets of passbands have the same routing properties through the filter 12.

The filter of FIG. 1 also includes a low resolution filter 13 which comprises an input waveguide 28 connected to a 1xN input frequency routing device 30. The device 30 has N output ports connected to respective ones of waveguides 32_1, 32_2, ..., 32_N. The waveguides 32_1, 32_2, ..., 32_N are connected to one side of each of a plurality of optical amplifiers 34_1, 34_2, ..., 34_N. The other side of each optical amplifier is connected to a respective one of a plurality of waveguides 36_1, 36_2, ..., 36_N which are, in turn, connected to respective input ports of an Nx1 output frequency routing device 38. A single output port of the frequency routing device 38 is connected to the waveguide 14 which thus directs the output of the low resolution filter 13 to the input of the high resolution filter 12. The low resolution filter 13 operates in a manner similar to that of high resolution filter 12. It takes a plurality of multiplexed input frequencies received on waveguide 28 and produces a subset of those multiplexed frequencies within one free spectral range of the high resolution filter 12 on waveguide 14 depending upon which one of the optical amplifiers 34_1, 34_2, ..., 34_N is activated by a gate control circuit 40. The low resolution filter 13 is dimensioned to give low resolution passbands separated by a frequency interval of $N\Delta F$, as shown in FIG. 3. Each one of the low resolution passbands overlaps one of the set of passbands FSR associated with the high resolution filter 12, as also illustrated in FIG. 3. There are thus N high resolution passbands within a single low resolution passband associated with the filter 13.

Activation of the ith gate of the high resolution filter 12 and the jth gate of the low resolution filter 13 selects the $(i^{th})_j$ high resolution passband, as shown in FIG. 4, between the input and the output of the filter of FIG. 1. For example, if it is desired that the filter of FIG. 1 be tuned to a frequency within a passband given a reference number 28 in FIG. 3, then the jth optical amplifier 34_j is biased by the gate control circuit 40 and the others of the optical amplifiers between the frequency routing devices 30 and 38 are unbiased so as to select the jth passband associated with the low resolution filter 13. Also, the optical amplifier 18_2 is biased by the gate control circuit 26 with the other optical amplifiers between the frequency routing devices 12 and 22 left unbiased in order to tune the filter of FIG. 1 to a frequency within the passband numbered 28 in FIG. 3. If it is the desired to tune the filter of FIG. 1 to a different frequency in a passband, such as passband numbered 29 in FIG. 3, associated with the high resolution filter 12, but in a different FSR,

then the optical amplifier between frequency routing devices 30 and 38 which selects the appropriate low resolution passband overlapping the desired FSR associated with the high resolution filter 12 is activated and the others of those optical amplifiers are kept unbiased. If it is desired to tune the filter of FIG. 1 to a different passband associated with the high resolution filter 12, but within the same FSR, such as the passband numbered 29 in FIG. 3, then the single activated amplifier between the frequency routing devices 12 and 22 is changed as appropriate. The activation of the amplifiers between the devices 30 and 38 is left unchanged.

Tuning is done digitally by means of electrical switching. It is expected to be very stable and can be made to switch at nanosecond speeds by using a fast electrical switch. Such a filter in front of a conventional direct detection optical filter provides a means to realize an optical receiver tunable over a wide frequency range.

Each optical amplifier in the device of FIG. 1 comprises a doped section of waveguide with controllable optical transmissivity. The doping may be such that an appropriately configured semiconductor junction is defined in each optical amplifier. These sections are optically active in that application of electrical energy to those sections will cause them to become transmissive to the flow of optical energy and will even provide some degree of gain to optical signals flowing through them. These doped sections of waveguide are substantially opaque to the transmission of light when there is no applied electrical stimulation. The specially doped sections thus may be considered to be gates or optical amplifiers depending upon whether or not they are excited with electrical energy. The details of creating such sections in a wafer such as the indium phosphide wafer 10 shown in FIG. 1 are generally known, are not a part of this invention, and thus are not described here.

FIG. 2 shows the pertinent details of an example of a routing devices 12, 22, 30, and 38 shown in FIG. 1. Each frequency routing device contains a plurality of input waveguides 26 connected to a free space region 28. A plurality of output waveguides 30 extends from the free space region 28 and is connected to an optical grating 32. The optical grating 32 comprises a plurality of unequal length waveguides which provides a predetermined amount of path length difference between the output waveguides 30 and a corresponding plurality of input waveguides 34 connected to another free space region 36. The free space region 36 is connected to a plurality of output waveguides 38. These frequency routing devices operate as different optical frequencies used in high speed, high capacity optical communications networks. For example, frequency routing devices with N up to 32 or more may be conveniently fabricated on a single semiconductive wafer. This results in a filter which

can be tuned to any of up to 32^2 or more optical frequencies. For example, assuming high and low resolution filters designed to give respective high and low resolution passbands separated by 50 GHz and 800 GHz, respectively, the device of FIG. 1 can be tuned to at least 256 discrete frequencies over a tuning range of 12,800 GHz (about 100 nm around a wavelength of 1.5 microns). The tuning range in this case is limited not by the size of the frequency routing devices but by the gain bandwidth of an active semiconductor medium. Devices such as the filter in FIG. 1 are attractive for large size optical network applications based on frequency division multiplexing.

Claims

1. A tunable optical filter, comprising:
    a first optical filter having a first frequency resolution formed in a semiconductive wafer; and
    a second optical filter having a second frequency resolution formed in the semiconductive wafer in series with the first optical filter.

2. The optical filter of claim 1, in which the first resolution is greater than the second resolution.

3. The optical filter of claim 1, in which each optical filter comprises an input frequency routing device in series with an output frequency routing device.

4. The optical filter of claim 3 in which each input frequency routing device is capable of receiving a multiplexed plurality of optical frequencies on an input waveguide and routing each frequency to a respective one of a plurality of output waveguides.

5. The optical filter of claim 3 in which each output frequency routing device is capable of receiving a single optical frequency on each of a plurality of input waveguides and multiplexing those optical frequencies onto a single output waveguide.

6. The optical filter of claim 1, further comprising:
    a plurality of waveguides connecting a plurality of outputs from each of the input frequency routing devices to a plurality of inputs of each of the output frequency routing devices;
    each of the plurality of waveguides comprising a controllably transmissive section.

7. The optical filter of claim 6, further comprising:
    a control circuit for selectively applying electrical energy to a predetermined one or more of the controllably transmissive sections for tuning the optical filter to a predetermined one or

more of the plurality of multiplexed optical frequencies received by the input frequency routing device.

8. The optical filter of claim 3, in which each of the input frequency routing devices comprises:

at least one input waveguide;

a first free space region connected to the at least one input waveguide;

a plurality of output waveguides connected to the first free space region;

an optical grating connected to the plurality of output waveguides comprising a plurality of unequal length waveguides;

a plurality of input waveguides connected to the optical grating;

a second free space region connected to the plurality of input waveguides connected to the optical grating; and

a plurality of output waveguides connected to the second free space region.

9. The optical filter of claim 3, in which each of the output frequency routing devices comprises:

a plurality of input waveguides;

a first free space region connected to the plurality of input waveguides;

a plurality of output waveguides connected to the first free space region;

an optical grating connected to the plurality of output waveguides comprising a plurality of unequal length waveguides;

a plurality of input waveguides connected to the optical grating;

a second free space region connected to the plurality of input waveguides connected to the optical grating; and

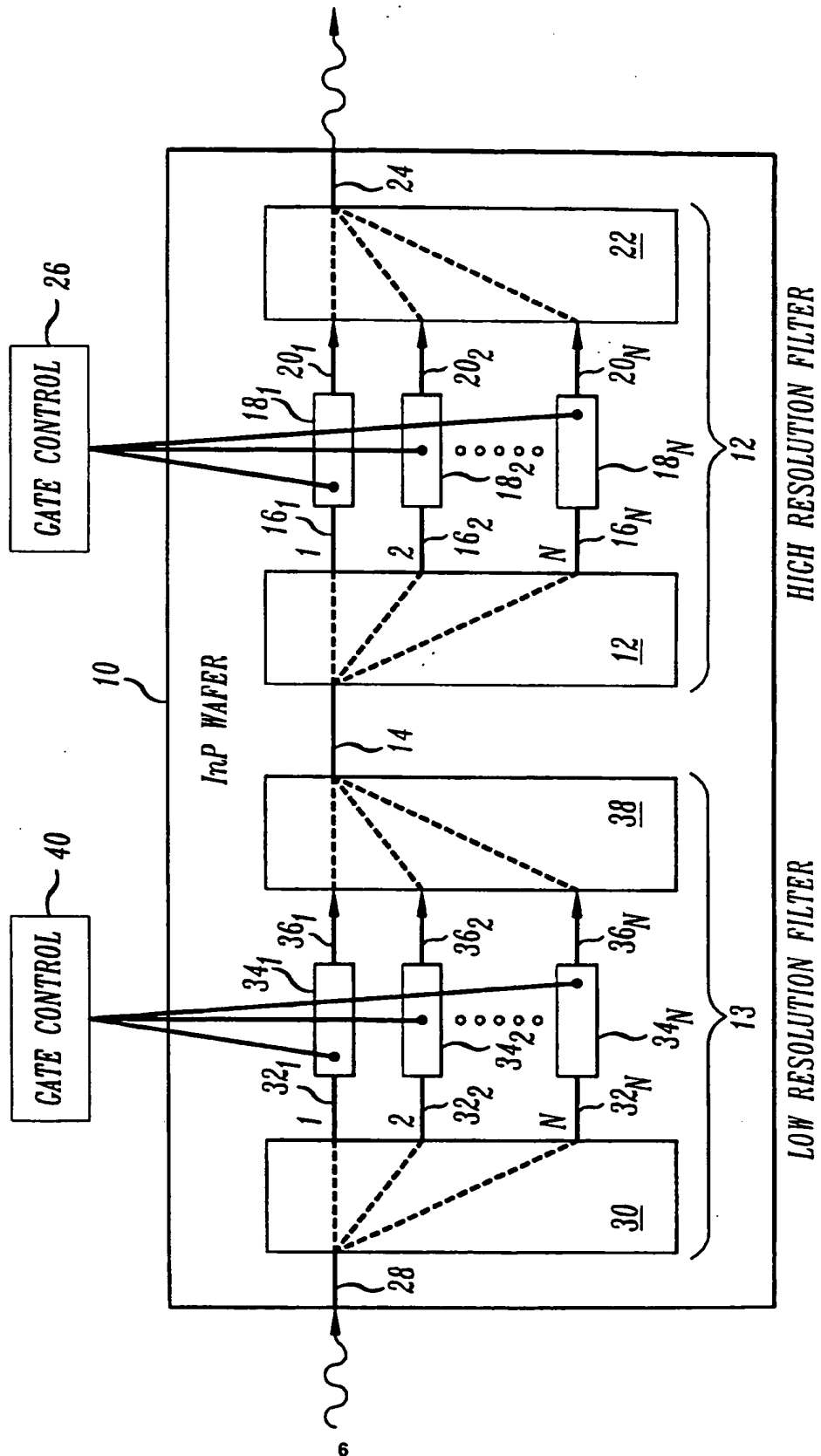at least one output waveguide connected to the second free space region.

FIG.1

FIG.2

GRATING 32

FIG.3

FREQUENCY ROUTING SEEN FROM ONE PORT

HIGH RESOLUTION PASSBANDS
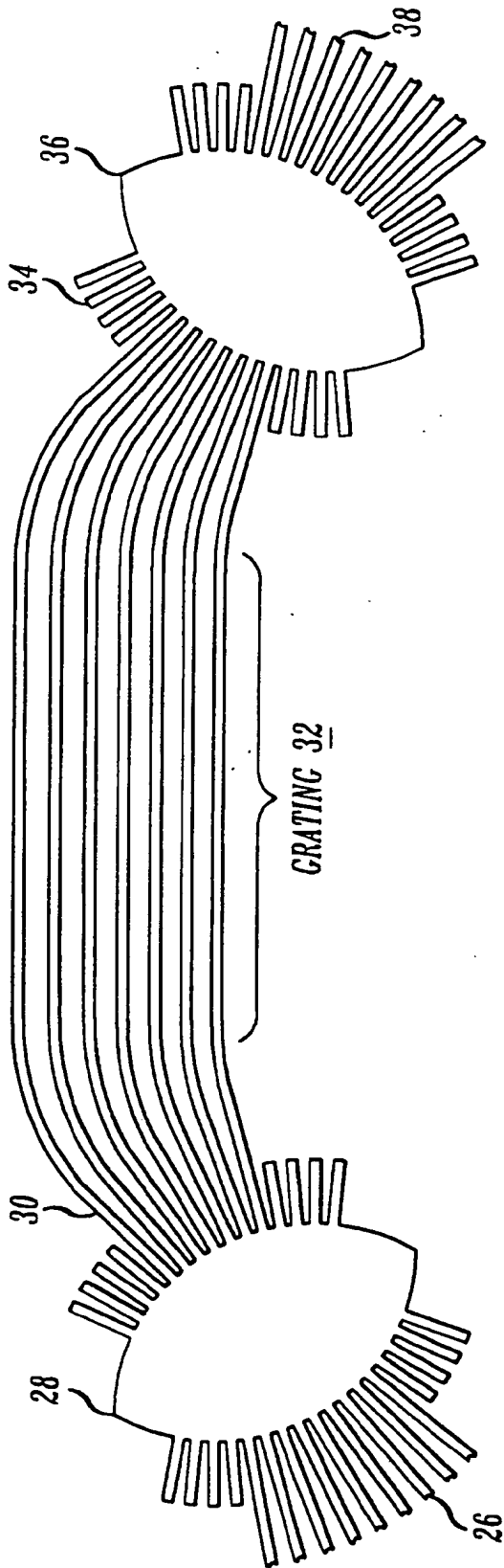
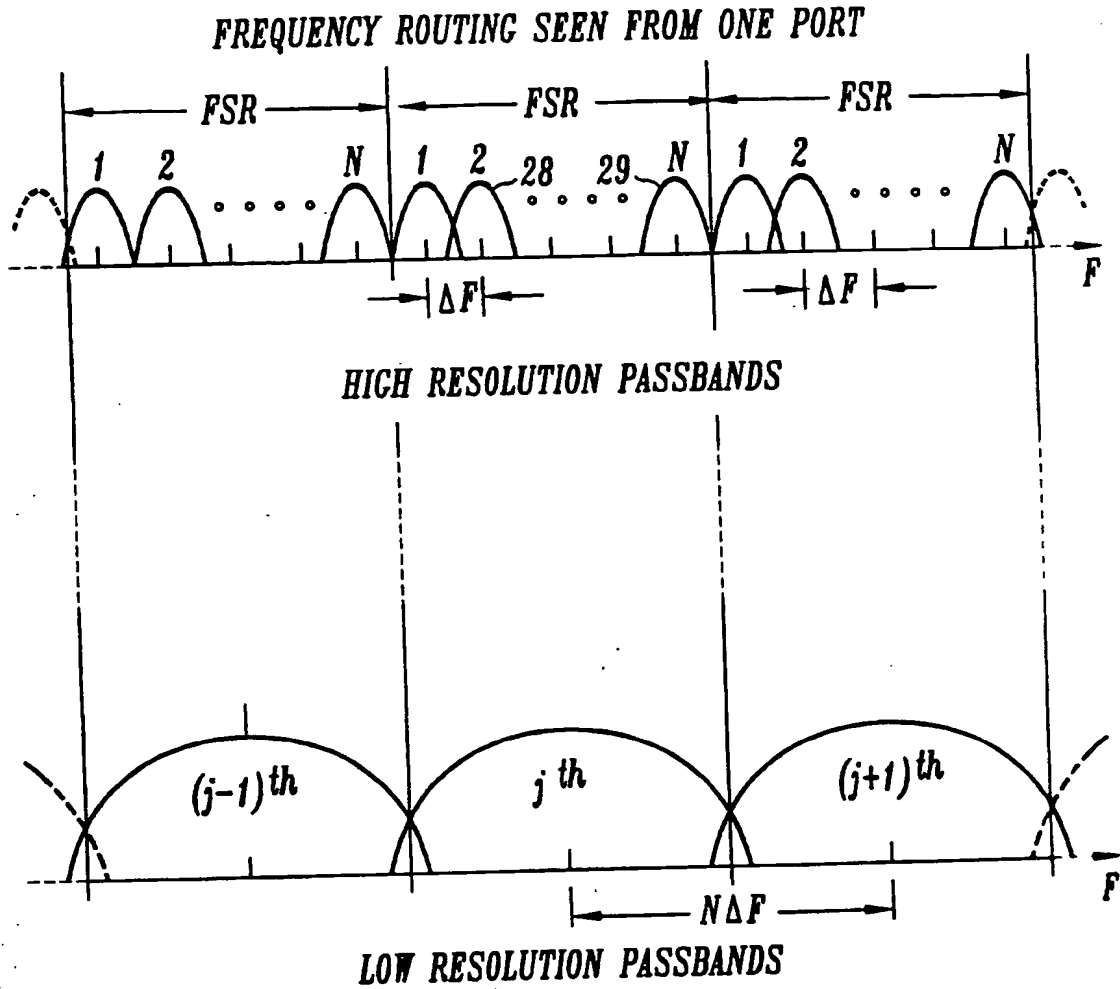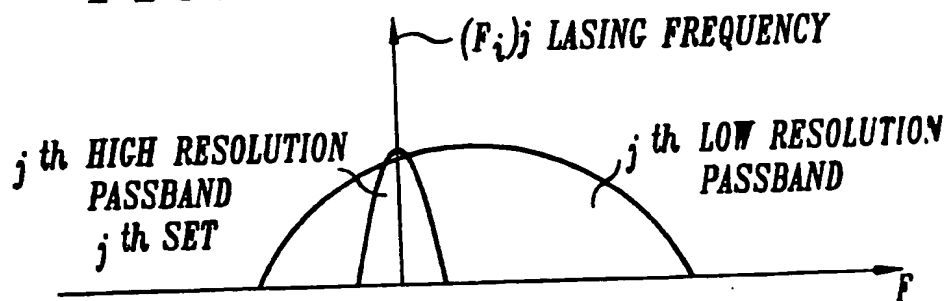LOW RESOLUTION PASSBANDS

FIG.4

European Patent
Office

EUROPEAN SEARCH REPORT

Application Number

EP 94 30 0939

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
X	EP-A-0 478 391 (OKI ELECTRIC IND.) * column 4, line 44 - line 57; figure 3 * * column 10, line 1 - column 12, line 52 * ---	1,2	H04J14/02 G02B5/20 G02B6/34 G02F1/313
X	EP-A-0 496 348 (CANON K.K.) * page 2, line 28 - line 41; figure 2 * * page 4, line 58 - page 5, line 17; figure 6 * ---	1	
X	PATENT ABSTRACTS OF JAPAN vol. 16, no. 495 (P-1436) 14 October 1992 & JP-A-04 178 613 (NEC) 25 June 1992 * abstract * ---	1	
A	ELECTRONICS LETTERS., vol.23, no.21, 8 October 1987, STEVENAGE GB pages 1102 - 1103 KAMINOW ET AL. * page 1102 * ---	2	
A	PATENT ABSTRACTS OF JAPAN vol. 7, no. 239 (E-206) 25 October 1983 & JP-A-58 129 849 (NIPPON DENSHI DENWA KOSHA) 3 August 1983 * abstract * ---	3-7	TECHNICAL FIELDS SEARCHED (Int.Cl.5) H04J G02B G02F H04Q
A,D	US-A-5 136 671 (DRAGONE) * column 6, line 1 - column 8, line 18; figure 1 * -----	8,9	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	30 May 1994	von Moers, F

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another
document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or
after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding
document

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